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COLUMBIA RIVER THERMAL EFFECTS STUDY. VOLUME 2. TEMPERATURE PREDICTION STUDIES

Environmental Protection Agency
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VOLUME II: TEMPERATURE PREDICTION STUDIES

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FOREWORD

The Columbia River Thermal Effects Study was undertaken in pursuit of the policies and objectives of the Federal Water Pollution Control Act, particularly as amended by the Federal Water Quality Act of 1965, which required the establishment of water quality standards for the protection and enhancement of water quality throughout the United States. In the process of establishing standards during the period 1965-1968, the State and Federal water pollution control agencies recognized water temperatures as an important factor affecting water uses, both directly, as in the case of aquatic life, and indirectly, as in the synergistic effects of temperature with other parameters such as dissolved oxygen. In attempting to define temperature requirements in the standards, however, pollution control authorities encountered insufficient scientific knowledge and agreement on the precise limits needed to protect water uses.

The Columbia River Thermal Effects Study was initiated in July, 1968, in response to the specific problem of two inconsistent temperature standards adopted for the Columbia River by the States of Oregon and Washington, which share it as a border. Before attempting to resolve these inconsistencies, the State and Federal pollution control agencies could benefit from improved knowledge on the temperature requirements and tolerances of the Columbia's Pacific salmon and improved techniques for evaluation and prediction of the temperature in the Columbia system. The report of the study consists of two volumes. The first concerns the biological effects of water temperature on Pacific anadromous fish in the Columbia River

system. The second describes the application of mathematical models to the Columbia River for prediction of water temperatures.

In the Pacific Northwest, standards were generally required to protect the economically important Pacific salmon, a cold-water anadromous species. The upriver runs of Columbia River fish resources have been reduced and endangered by the physical alteration and blockage of migration routes by the Nation's largest system of dams and reservoirs. The quality of the aquatic environment has also been modified by the discharge of pollutants and impoundment of the river's flow in a series of reservoir lakes reaching into Canada. Particularly regarding temperature quality, the Columbia River temperatures have been both spatially and temporally altered by man's activities and use of the water resources of the Region.

At about the time standards were established, public and private electric power interests in the Northwest announced forecasts of vastly increased power demands. The hydroelectric power potential of the Northwest is nearly exhausted, and thermal power sources are planned to meet future needs. This presented further potential for modification of the thermal regime of the Columbia River system. Initially, power producers assumed the possibility of using Columbia River system waters for once-through cooling at thermal power plants. The prospect, however, of numerous discharges of large quantities of heated effluents to inland waters has since prompted the Region's water pollution control agencies to issue policy statements which require complete offstream cooling for thermal power plants located

on inland waterways in the Basin. Power planners have accepted this policy of offstream heat controls throughout the Basin.

Among the remaining environmental problems associated with increased thermal power production is the projected use of the existing hydroelectric system for power-peaking, with thermal units providing the baseload, or firm power. The potential water quality effects of exaggerated flow modification caused by these peaking operations emphasizes the need to understand the existing thermal regime of the Columbia River system. The prospects of industrialization, upon which the power demands are based, hold further potential for environmental impacts which would require sound standards and controls.

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INTRODUCTION

Purpose

This report describes the application of the mathematical models which were adapted to the Columbia River as part of the Columbia River Thermal Effects Study. The models provide a tool for predicting river temperatures as a function of flow regulation and point-source thermal inputs.

The physical, chemical, and biological characteristics of water are highly dependent on water temperature. Important examples include the effects of temperature upon: 1) the solubility of gases such as oxygen and nitrogen; 2) the stages of fish development; 3) the growth rate of algae; 4) the taste and odor of water; and 5) the density and stratification of water bodies. Spatial and temporal changes in water temperature, even though subtle, may disturb the life systems which have developed under natural conditions. In the Columbia River mainstem, changes in the natural temperature regime have been noted by Goebel and Jaske (1967), Davidson (1969), and Moore (1968). The most significant changes have been in the Columbia River above its confluence with the Snake River. The principal effect has been the shifting of water temperature maximums so that they occur later in the year. The resulting temperatures are above the optimums for salmonids during September and October, according to criteria recommended by the Pacific Northwest Pollution Control Council (1966).

The construction of numerous dams has been attributed as the primary cause of this change in the temperature regime; the discharge of cooling water from nuclear power plants on the Hanford Reservation

in southeastern Washington has also been a contributing factor. Proposals for additional storage in the Canadian treaty dams, the construction of a third powerhouse at Grand Coulee Dam, and the proposed construction of Ben Franklin Dam in the last unimpounded reach of the river offer potential for further modification of the river's temperature.

The temperature prediction models described in this report provide a valuable input for developing a river management system which considers the effects of reservoir releases on water quality. The reservoir projects in the Columbia River Basin are operated primarily for power, flood control, irrigation, and navigation. The temperature models can be used to evaluate the effects of a given water management scheme on an important aspect of water quality. The capability to predict the effect of reservoir release schedules provides water management agencies the opportunity to influence the timing and method of withdrawals to minimize adverse temperature changes in the Columbia River. The models can also be expanded to include other water quality parameters such as dissolved oxygen and nitrogen. A water management system which considers water quality can be a powerful tool in developing release schedules to enhance the fishery and at the same time optimize flow release for competing water uses, such as power generation, irrigation, and flood control.

The models can be used as a planning as well as an operational tool. The capability to forecast the impact of future projects on water temperature, using advanced techniques for hydrologic forecasting

and the generation of synthetic weather data has been demonstrated. In this respect, the mathematical models which have been developed are sufficiently general so as to be usable in systems other than the Columbia Basin.

Scope

The Temperature Prediction Study enlarged upon earlier work performed by the Environmental Protection Agency (EPA) which concentrated on the river-run reservoirs of the mid-Columbia. The scope of the present study has been to adapt, verify, and maintain an operational system of mathematical models of the Columbia River from the Canadian border to the river's mouth. The variation in hydraulic characteristics along the river requires that these models be capable of predicting temperatures in river-run reservoirs, in deep reservoirs, and in the estuary. The intent was, insofar as practicable, to adapt available models to the conditions encountered in the Columbia River. Under contract with EPA, Water Resources Engineers, Inc. modified the deep reservoir model they had developed for application to Columbia Basin Projects. The estuary model, originally developed by Water Resources Engineers, Inc., was adapted for use on the Columbia River estuary by the EPA's Coastal Pollution Research Program, Pacific Northwest Water Laboratory, Corvallis, Oregon.

Development of a water temperature measurement and reporting program was also included to provide a means for verifying the models.

Authority

The Columbia River Thermal Effects Study (CRTES) was authorized by the Secretary of the Interior in February, 1968.[1/] In his approval of the water quality standards for the State of Washington, the Secretary recognized that the temperature criteria set by the State for the Columbia River were inconsistent with those set by the State of Oregon for the same waters. Rather than disapprove the temperature criteria portion of Washington's standards, the Secretary directed that the Thermal Effects Study be completed to provide further knowledge with which to reconsider the adequacy of temperature criteria for the Columbia River.

The Northwest Regional Office of the Environmental Protection Agency was directed to provide leadership in the study. The Temperature Prediction portion of the CRTES was coordinated through the Water Supply and Pollution Control Committee of the Pacific Northwest River Basins Commission.

1/ On December 3, 1970, the Presidential Order creating an independent Environmental Protection Agency took effect. The EPA incorporates many Federal programs concerning the environment, including water pollution control. The Federal Water Quality Administration (formerly the Federal Water Pollution Control Administration) in the Department of Interior was abolished and the water pollution control responsibilities and authorities of the Secretary of the Interior were transferred to the Administrator of EPA.

II. SUMMARY

General

Three numerical models have been adapted to predict temperatures in the main stem Columbia River, extending 750 miles from the Canadian border to the mouth of the river at Astoria, Oregon. These three models facilitate prediction of temperatures in the four hydraulic regimes which comprise the main stem Columbia in the United States. The models are:

1. The weakly stratified reservoir model is a more sophisticated version of the one-dimensional deep reservoir model developed by Water Resources Engineers, Inc. (Orlob and Selna, 1968). In the weakly stratified reservoir, the vertical variation of temperature is the same order of magnitude as the horizontal variation. Lake Roosevelt, behind Grand Coulee Dam, is a weakly stratified reservoir.

2. The river-run reservoir model was developed by the EPA for reservoirs which are well-mixed vertically and laterally, but which have a longtudinal temperature variation. The reservoirs between Grand Coulee and Bonneville Dams are of this type. This model is also used for the unimpounded reach of the Columbia River. If averages over a tidal cycle are sufficient for application, this model can be used in the estuary as well.

3. The estuary model was adapted by the EPA (Callaway, 1970) from a model developed by Water Resources Engineers, Inc. for the San Francisco Bay-Delta region. The Columbia River estuary includes the river from Bonneville Dam to the mouth at Astoria, Oregon. The

estuary, which is affected by tidal forces, may be stratified vertically due to the intrusion of high salinity ocean water. In the Columbia River estuary only the first 25 miles are considered to be vertically stratified.

The computer software (programming) for the weakly-stratified reservoir model and the river-run reservoir model, as well as the necessary hydraulic, hydrologic, and meteorologic data constitutes the Columbia River temperature model. This model will be used to simulate and predict daily averaged temperatures on the Columbia River from the U. S.-Canadian border to the mouth of the river at Astoria, Oregon. For those cases in which smaller time scales are important, the estuary model can be used. This would be necessary, for example, if maximum and minimum temperatures during a tidal cycle were needed.

Conclusions

From the test runs of the Columbia River temperature prediction model, the following is concluded:

1. The Columbia River temperature model, consisting of the weakly-stratified and the river-run reservoir models, has been verified to simulate river temperatures from the Canadian-U. S. border to Bonneville Dam. For six simulations with differing input conditions, the maximum average error was 1.2° F and the maximum standard deviation was 2.4° F.

2. For a release temperature at Grand Coulee Dam 5° F below the 1967 observed temperature, the temperature at the Snake River confluence

was reduced 3.8° F on the average, and 1.5° F on the average at Bonneville Dam. However, the amount of temperature reduction available downstream from Grand Coulee varies considerably with time; it is smallest in late summer and fall when conditions are most critical for migrating salmon.

3. The weakly-stratified reservoir model contributed 12 percent of the total downstream temperature error at the Snake River and 17 percent of the total error at Bonneville Dam. The major error contribution occurs during the time of fall reservoir turnover, when the prediction capabilities of the weakly-strafitied model are poorest.

4. From April through November, 1967, the heat added to the river from the Hanford reactor complex raised the simulated water temperature an average of 2° F at the confluence of the Columbia and Snake Rivers.

5. A more precise simulation of the Columbia River temperature will require more detailed information on hot water release schedules from the Hanford complex.

6. The river-run model is adequate for simulating tidally-averaged temperatures in the Columbia River estuary. The error associated with the estimate at Bonneville Dam and at Beaver Army Terminal was $\pm$ 0.2° F.

7. The effect of evaporation is most significant from the first of August to the end of November. Prior to that time the empirical coefficients in the evaporation equation can vary two orders of magnitude without significantly affecting the accuracy of temperature simulation. After the first of August, evaporation begins to play an important role in heat budget and the determination of the correct coefficient becomes critical.

Recommendations

1. The models should be used to evaluate the potential for temperature control using upriver storage. This could be accomplished in conjunction with a program such as the Streamflow Synthesis and Reservoir Regulation (SSARR) system. The U. S. Army Corps of Engineers, North Pacific Division, and the National Weather Service, National Oceanic and Atmospheric Administration, developed this program which is presently used to operate the hydroelectric projects on the Columbia.

2. The effects of impoundments in the Columbia River in Canada and on the main stem Snake River should be incorporated into the temperature prediction model.

3. High temperature release schedules from the Hanford area should be made available to better predict the river's thermal regime.

4. The weakly-stratified and river-run reservoir models should be applied to other river basins for purposes of planning and water quality control.

5. Continued study of evaporation processes at the air-water interface would benefit the heat budget approach to temperature prediction.

III. HYDROLOGY, METEOROLOGY AND GEOGRAPHY OF THE COLUMBIA RIVER BASIN

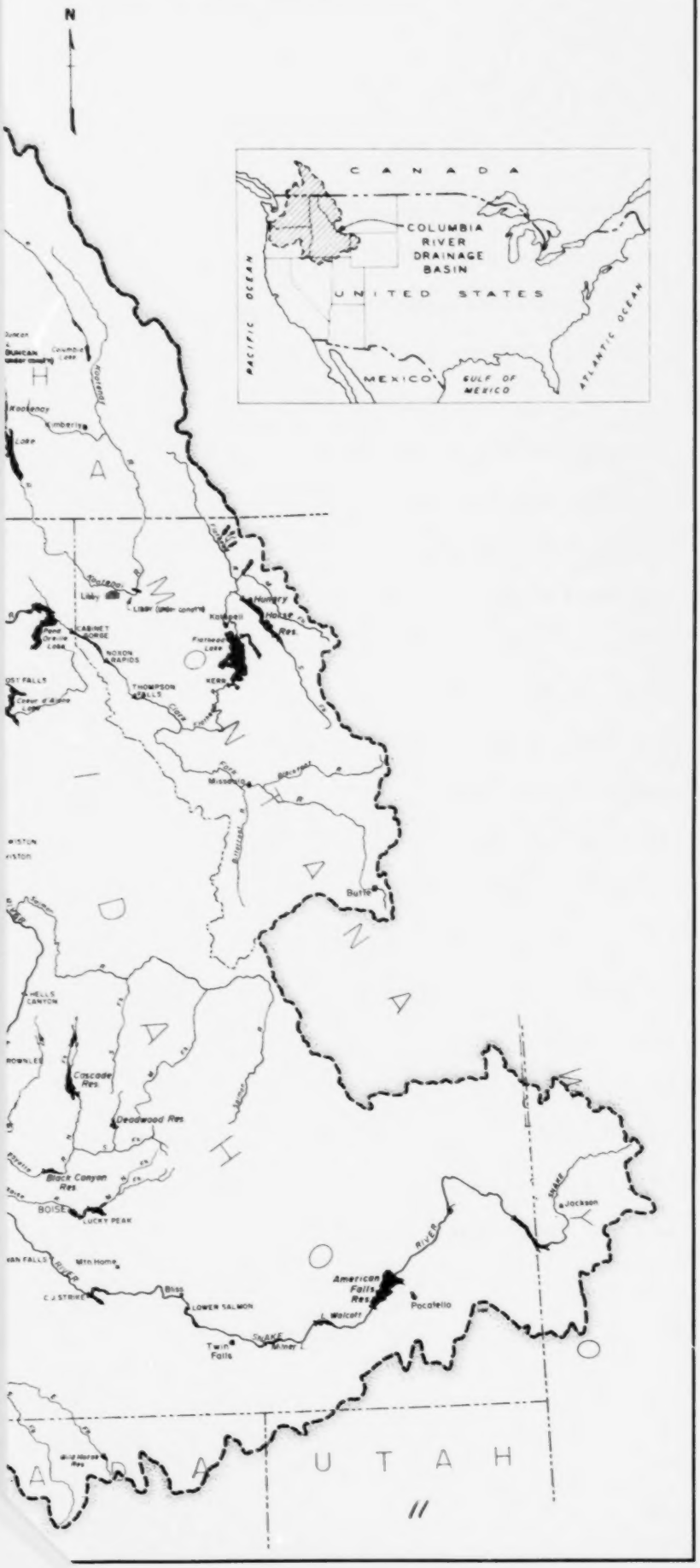
Geography

The Columbia River drains 259,000 square miles in the Pacific Northwest States of the United States and southeastern British Columbia in Canada (Figure 1). The area is characterized by rugged mountain ranges interspersed with valleys and plains. Stream gradients are generally steep, and mountain torrents which originate in headwater areas flow quickly down to the valleys where they join major tributary rivers. The interior Columbia Basin and Snake Plain are flat, arid, and relatively low plateaus lying within the surrounding mountain areas. The Columbia and Kootenai River drainages in Canada are extremely rugged mountain areas, dotted with glaciers and ice fields in the higher and wetter locations. Along the coastal regions of western Oregon and Washington the north-south Cascade Range forms an effective barrier between the interior and the relatively minor coastal sections.

Stream System

The main stem of the Columbia River heads in Canada at Columbia Lake, British Columbia, and flows north to the Big Bend. Then it flows south about 130 miles to the Arrow Lakes, through which the river flows 110 miles to the outlet of the Lower Arrow Lake near Castlegar, British Columbia. The Columbia River continues its

FIGURE 1
Columbia River Basin


N
CANADA
COLUMBIA RIVER DRAINAGE BASIN
UNITED STATES
PACIFIC OCEAN
ATLANTIC OCEAN
MEXICO
GULF OF MEXICO
Libby
Kalispell
Hungry Horse Res.
CABINET GORGE
NOXON RAPIDS
THOMPSON FALLS
Missoula
Butte
HELLS CANYON
Cascade Res.
Deadwood Res.
Black Canyon Res.
BOISE
LUCKY PEAK
Mtn. Home
C.J. STRIKE
Bliss
LOWER SALMON
Twin Falls
Wilcox
American Falls Res.
Pocatello
Jackson
UTAH

route generally in a southerly direction to the Canadian border, traverses the State of Washington through the Columbia Basin, and finally flows west to form the border between Oregon and Washington. The slope of the river under natural conditions is fairly steep, with an average gradient in excess of two feet per mile.

The major tributaries of the Columbia River include the Kootenai, Clark Fork-Pend Oreille, Spokane, Snake, and Willamette Rivers. The Kootenai lies largely in Canada, but flows southward in the United States, making an arc through western Montana and northern Idaho, and flowing north back into Canada. It flows through Kootenay Lake, a major natural lake in south-central British Columbia. The Kootenai River continues west from the outlet of Kootenay Lake to join the Columbia below Lower Arrow Lake.

The Clark Fork-Pend Oreille system drains a large part of western Montana. The Clark Fork heads in the Continental Divide and flows northwest into Idaho where it terminates in Pend Oreille Lake, another large natural lake in the Columbia River system. The outflow from Pend Oreille Lake becomes the source of the Pend Oreille River, which flows north about 75 miles to the Canadian border. It then flows west about 16 miles to its junction with the Columbia River. The Flathead, Blackfoot, and Bitterroot Rivers are all major tributaries of the Clark Fork. Flathead Lake, located on the Lower Flathead River, is another large body of water which affects storage and flow of water in the Columbia River system.

The Snake River drainage is the largest of all Columbia River tributaries. The Snake River heads in western Wyoming in Yellowstone National Park and flows west through the arid Snake River plains of southern Idaho. Then it turns north, forming the boundary between Oregon and Idaho. The Salmon and Clearwater Rivers join the Snake River from the east, after which the river emerges into the Interior Columbia Basin. The Lower Snake River trends in an arc about 140 miles through southeastern Washington, to join the Columbia near Pasco, Washington.

Climate

The climate of the Columbia Basin is characterized by cold, wet winters and generally hot, dry summers. Precipitation varies widely, depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 10 inches per year, but in some of the mountain areas of Canada the annual precipitation exceeds 100 inches per year. Air temperature also varies widely with location. In the relatively low Columbia Basin and Snake Plain, summertime maximums often exceed 100° F for prolonged periods. In the mountains of Canada temperatures remain cool during the summer. Winters are generally cold throughout the basin, and heavy precipitation falls in the form of snow in the mountain areas. The snowpack accumulates throughout the winter as the result of frequent passage of storms from the Pacific, and the snow does not melt appreciably until April or May. Precipitation

is at a maximum during the winter months for the basin as a whole, but a secondary maximum occurs in June in the Rocky Mountain areas in the eastern portion of the basin. Winters are cloudy, and solar radiation is at a minimum, until the arrival of spring. Solar radiation is at a maximum in June and July, and clear skies prevail in the plains throughout the summer. Convection activity in the mountains results in summer build-up of clouds and shower activity in the afternoons. Occasionally, general storms from the Pacific invade the northern portions of the basin during the summer.

Western Oregon and Washington have moderate climates with winter air temperatures at low elevations seldom below freezing and summer air temperatures seldom above 100° F for prolonged periods. Average annual precipitation west of the Cascades is greater than 40 inches in most areas. Coastal stations are typically much higher; for example, Astoria, Oregon has an average annual rainfall of 80 inches. Below 5000 feet, most of this precipitation occurs as rainfall with 70 percent or more occurring between October and March.

Hydrology

Surface runoff in the Columbia River Basin is characterized by a typical snowmelt regime. Low streamflows prevail during the winter, and high flows during the spring and early summer, particularly in the elevated basins. Melting of the winter snowpack accumulation takes place in May and June, and streamflows rise until the snowpack

can no longer support the high flows. The streamflow recedes gradually during the summer, and the flows are derived from ground water recession into the fall and winter seasons. Occasionally, runoff from winter storms augments the base flow, and significant rises may occur. With the exception of the Willamette, these rises are of relatively short duration and are not of the general magnitude of the rises during the spring snowmelt.

In the Willamette River system, peak flows occur in December, January, and February, corresponding to the period of heaviest rainfall in this region. Snowmelt at the higher elevations during May and June contributes to relatively high runoff during this period.

Mean monthly and mean annual discharges for key locations on the main stem and tributaries are given in Table 1.

TABLE 1

MEAN DISCHARGES AT KEY LOCATIONS FOR THE PERIOD OF RECORD

River	Location	Mean Monthly Discharge in cfs					Mean Annual cfs
		Jan	Apr	Jun	Aug	Oct	
Columbia	Revelstoke,B.C.	5,400	13,300	84,800	58,100	17,600	33,900
	Birchbank,B.C.	19,900	34,900	203,200	102,800	42,400	71,000
	Trinidad,Wash.	44,900	88,200	318,400	137,300	60,600	116,900
	The Dalles,Ore.	95,700	201,800	494,700	187,300	99,100	195,400
Kootenai	Libby,Montana	3,500	11,200	44,600	10,500	7,100	13,600
	Nelson,B.C.	10,100	20,100	89,900	23,200	13,200	28,000
Clark Fork-Pend Oreille	Plains,Montana	10,000	19,100	59,300	11,000	9,300	19,600
	Z-Canyon,Idaho	14,700	26,900	76,700	17,300	12,400	26,900
Spokane	Long Lake,Wash.	6,900	17,100	11,800	2,100	3,000	8,100
Snake	Weiser,Idaho	15,000	27,700	27,400	9.100	13,500	17,700
Snake	Clarkston,Wash.	29,800	84,500	110,800	19,500	23,400	48,900
Willamette	Portland,Ore.	78,100	46,900	20,200	5,200	10,100	32,100

Water Resource Development

The Columbia River and its tributaries are a highly developed water resource. The only portion of the River which is not impounded is the reach between Priest Rapids Dam and the confluence of the Snake River. The 11 main-stem projects, from Grand Coulee to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head in this reach of the Columbia. The completion of the four Columbia Treaty reservoir projects in Canada and the United States will result in significant control of flows in the Upper Columbia and Kootenai River Basins (the Columbia Treaty between the United States and Canada relates to the Cooperative development of the Columbia River Basin water resources). Nine major projects have been completed on the Clark Fork-Pend Oreille systems, which, with the completion of Boundary Project in the Lower Clark Fork, will develop a large part of the power potential in that basin. The Snake River below Weiser, Idaho, is also fast approaching full development, except for those streams presently reserved from development in the interest of preservation of fish and wildlife. The water resources of the Snake River Basin above Weiser are largely developed in the interest of irrigation, power, and flood control.

The ownership of the dams in the Columbia River Basin includes Federal agencies, private power companies, and public utility districts. The installed capacity of the hydro-electric projects existing or under construction in the Pacific Northwest is about

20,000,000 kilowatts (kw), of which about one-half is in Federal projects. Thermal generation of electricity is relatively small at the present level of development (about 1,200,000 kw of installed capacity, including 800,000 kw at Hanford) and it is used primarily to supplement hydro-electric generation in periods of low streamflow.

The dams and reservoirs are multiple purpose, serving the functions of irrigation, navigation, flood control, preservation of fish and wildlife, municipal and industrial water supply, and recreation, as well as hydro-electric power. Irrigation presently includes providing water for agricultural use to approximately 5,000,000 acres of land; and plans call for an additional 5,000,000 acres to be irrigated in the next 50 years. Slack-water navigation is planned to extend 330 miles up the Columbia River to Pasco, Washington, and an additional 140 miles up the Snake River to Lewiston, Idaho.

Table 2 presents a list of major dams and reservoirs, by tributaries, which may have an effect upon water temperature studies.

TABLE 2

MAJOR DAMS AND RESERVOIRS, COLUMBIA RIVER BASIN

Stream	River Mile	Project Name	Owner or Operator	Status	Active Stor. Acre-Feet	Primary Proj. Function
Columbia River	1018.1	Mica	B.C. Hydro Authority	UC*	12,000,000	Power, Flood Control
	780.6	Arrow Lake	B.C. Hydro Authority	UC	7,100,000	Power, Flood Control
	596.6	Grand Coulee	U.S. Bureau of Reclam.	C	5,232,000	Irrig., Power, Fl. Con.
	545.1	Chief Joseph	U.S. Corps of Engineers	C	Pondage	Power, Irrigation
	516.6	Wells	Douglas County PUD	C	Pondage	Power
	474.5	Rocky Reach	Chelan County PUD	C	Pondage	Power
	453.4	Rock Island	Chelan County PUD	C	Pondage	Power
	415.0	Wanapum	Grant County PUD	C	330,000	Power, Flood Control
	397.1	Priest Rapids	Grant County PUD	C	170,000	Power, Flood Control
	292.0	McNary	U.S. Corps of Engineers	C	Pondage	Power, Navigation
	215.6	John Day	U.S. Corps of Engineers	C	500,000	Power, Navigation, Flood Control
	191.5	The Dalles	U.S. Corps of Engineers	C	Pondage	Power, Navigation
	146.1	Bonneville	U.S. Corps of Engineers	C	Pondage	Power, Navigation
Kootenay River	219.9	Libby	U.S. Corps of Engineers	UC	4,965,000	Power, Flood Control
	16.1	Corra Linn	Consolidated Mining and Smelting Company	C	817,000	Power, Flood Control
Duncan River	8.3	Duncan Lake	B.C. Hydro Authority	UC	1,400,000	Power, Flood Control
So. Fk. Flathead	5.2	Hungry Horse	U.S. Bureau of Reclam.	C	2,982,000	Power, Flood Control
Flathead River	72.0	Kerr (Flathead Lake)	Montana Power Company	C	1,219,000	Power, Flood Control
Clark Fork	208.0	Thompson Falls	Montana Power Company	C	Pondage	Power
	169.7	Noxon Rapids	Washington Water Power	C	231,000	Power, Flood Control
	149.9	Cabinet Gorge	Washington Water Power	C	Pondage	Power
Priest River	44	Priest Lake	Washington Water Power	C	72,401	Power

*UC-Under Construction
C-Constructed

IV. WATER TEMPERATURE REGIME OF THE COLUMBIA, SNAKE, AND WILLAMETTE RIVERS

The temperature regime of major streams in the Columbia River Basin has been modified by the construction and operation of numerous dams and by water uses such as irrigation and power plant cooling.

Existing thermal characteristics of many streams in the basin, as well as some historical changes on a few streams, are evidenced by recorded water temperature data. Since the emphasis on water temperature observations is relatively new, only a few stations in the basin have long term daily records. While records of spot observations at some locations go as far back as 1915, regular observations did not commence until the 1930's. These early observations consisted of once daily or twice daily readings. Often the time of observation was not recorded and it is therefore not possible to relate the observed temperature to a corresponding point in the dirunal cycle. In the mid-1940's, the introduction of recording hydrothermographs in the basin enabled a significant expansion in systematic water temperature observations. The instruments needed only periodic servicing and it was possible to locate them away from populated areas, thus increasing the number of water temperature stations and also giving them a wider distribution. By providing a continuous record, information on diurnal as well as annual variations in stream temperature is obtained.

This coverage has been extended by the Regional Temperature Reporting Network, a part of the Columbia River Thermal Effects Study (Schmidt and Cleary, 1969). The stations installed under this program provide continuous records of temperatures at selected sites. The U.S. Geological Survey, Battelle Northwest, the U. S. Army Corps of Engineers, and public utility districts provide temperature monitoring at other sites. Table 3 shows all the sites on the main stem Columbia at which temperatures are reported. The U. S. Geological Survey summarizes and reports most of the temperature data on a weekly, monthly, and annual basis. Each year they publish a comprehensive report of the temperature regime of the main stem Columbia, as well as the Snake River. Table 4 shows monthly water temperatures for calendar year 1967 at selected stations in the Columbia River Basin.

The Columbia River in Canada

Until October, 1968, when Arrow Lake Dam was completed, the temperature regime of the Columbia River in Canada was unaltered from the natural state. Temperature records available prior to October, 1968, at Trail, B. C. indicate that the annual temperature range was between 35° and 66° F, with the minimum occurring in February and the maximum in August.

Future temperatures of the Columbia River in Canada will be affected by the regulation of Mica and Arrow Lake Dams on the main stem Columbia, Duncan Dam on Duncan Creek in the Kootenay River Basin, and Libby Dam on the Kootenai River in Montana. These dams are under construction and will be completed in 1973.

TABLE 3

TEMPERATURE REPORTING AND RECORDING STATIONS ON THE COLUMBIA RIVER AND MAJOR TRIBUTARIES

Station	River	River Mile (RM)	Type of Sensing Devise	Owner/Cooperating agency
Harrington Point	Columbia	23.5	7 day chart thermograph	FWQA
Beaver Army Terminal	Columbia	53.8	7 day chart thermograph	PGE/Battelle N. W./USGS
Longview, Wash.	Columbia	66.0	7 day chart thermograph	PGE/Battelle N. W./USGS
Kalama, Wash.	Columbia	74.8	7 day chart thermograph	Clarke & Cowlitz Co. P.U.D./USGS
Columbia City, Ore.	Columbia	84.0	7 day chart thermograph	Corps of Engineers/USGS
St. John Bridge, Ore.	Willamette	6.0	7 day chart thermograph	FWQA
Vancouver, Wash.	Columbia	106.5	7 day chart thermograph	Corps of Engineers/USGS
Warrendale, Ore.	Columbia	141.0	7 day chart thermograph	AEC/Battelle N. W./USGS
The Dalles, Ore.	Columbia	192.8	7 day chart thermograph	FWQA
Biggs Rapids, Wash.	Columbia	208.0	7 day chart thermograph	AEC/Battelle N. W.
Umatilla Bridge	Columbia	290.5	7 day chart thermograph	AEC/Battelle N. W.
Ice Harbor Dam	Snake	9.7	7 day chart thermograph	FWQA
Richland, Wash.	Columbia	340.0	7 day chart thermograph	AEC/Battelle N. W.
Priest Rapids Dam, Wash.	Columbia	395.0	7 day chart thermograph	AEC/Battelle N. W.
Wanapum Dam, Wash.	Columbia	415.0	Punch Tape thermograph	FWQA
Rock Island Dam, Wash.	Columbia	453.4	Punch Tape thermograph	FWQA
Rocky Reach Dam	Columbia	474.5	Punch Tape thermograph	FWQA
Chief Joseph Dam	Columbia	545.1	7 day chart thermograph	FWQA
Grand Coulee Dam	Columbia	596.0	7 day chart thermograph	AEC/Battelle N. W.
Little Falls Dam	Spokane	30.0	7 day chart thermograph	FWQA
Northport, Wash.	Columbia	734.1	7 day chart thermograph	AEC/Battelle N. W.

TABLE 4
MONTHLY WATER TEMPERATURES (^{o}F) IN THE COLUMBIA RIVER BASIN
AT SELECTED STATIONS, CALENDAR YEAR 1967 a/

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Columbia River at Revelstoke, British Columbia	----	----	-----	-----	---	----	----	43	42	----	----	32
Columbia River at Trail, British Columbia	39	38	40	45	49	53	58	64	62	56	49	42
Columbia River at Northport, Washington (International Border)	37	39	41	41	48	----	58	64	62	55	46	39
Columbia River below Grand Coulee Dam, Washington	45	41	40	42	46	54	58	62	64	64	57	48
Columbia River below Priest Rapids Dam, Washington	43	42	41	45	50	56	61	65	64	60	52	45
Columbia River above Richland, Washington	45	45	44	48	54	56	62	68	67	61	54	46
Snake River at Brownlee Dam, Idaho	40	38	42	48	54	61	68	68	70	62	51	43
Snake River at Ice Harbor Dam, Washington	41	40	44	49	53	56	69	75	71	61	49	41
Columbia River at Bonneville Dam, Oregon	44	44	45	49	55	59	65	70	69	61	51	44
Willamette River at Salem, Oregon	45	45	46	50	58	----	69	71	65	56	53	44
Columbia River at Beaver Army Terminal, Oregon	44	44	45	50	56	----	----	72	70	60	50	42

a/ Published monthly by Northwest Water Resources Data Center, Water Resources Division, U. S. Geological Survey

Lake Roosevelt

Lake Roosevelt is the reservoir formed by Grand Coulee Dam. Lake Roosevelt is approximately 150 miles long, stretching from River Mile 596 to the U.S.-Canadian Border. It has a maximum depth of 350 feet and, with a total storage capacity of 9,000,000 acre-feet, is the largest impoundment on the main stem Columbia.

In summer the reservoir becomes stratified. Temperature differences of 12 to 13° F between top and bottom have been observed during September (Jaske and Snyder, 1967). In the fall this stratification pattern gives way to a temperature profile more characteristic of river-run reservoirs; that is, the longitudinal temperature variation is greater than the vertical variation.

Grand Coulee Dam to Priest Rapids Dam

The vertical stratification which occurs in the summer and early fall in Lake Roosevelt has a significant effect on downstream temperatures of the Columbia River. The cool bottom waters are discharged through the turbines during the summer, resulting in outlet temperatures which are lower than natural river conditions. In the late summer and fall, when the reservoir begins to overturn, the warmer surface waters begin to affect outflow temperatures, resulting in temperatures which are higher than natural river temperatures. Jaske and Goebel (1967) have shown that construction of Grand Coulee Dam has resulted in a phase shift of the water temperature maximums at Rock Island Dam. The maximum water temperature at Rock Island occurs 30 days later on the average, than it did prior to the construction of

Grand Coulee Dam. Similar results have been obtained by Davidson (1969) and Sylvester (1963). Figure 5 shows monthly outlet temperature ranges at Grand Coulee Dam for 1967.

The future thermal effects of Lake Roosevelt will depend upon three principal factors: the influence of Canadian impoundments on the thermal regime of Lake Roosevelt; the thermal effect of the third power house under construction at Grand Coulee Dam; and, perhaps the most significant factor, the use of selective withdrawals for downstream temperature control. Releases can be made from four levels at Grand Coulee, in addition to the spillway. The third power house is an important factor because its turbine intakes will be located closer to the surface of the reservoir than those of the two existing power houses.

There are six pools between Grand Coulee and Priest Rapids Dam: Chief Joseph, Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids. Chief Joseph has a maximum depth of 165 feet. Depths of the remaining five reservoirs range from 54 to 93 feet at their deepest points.

These six reservoirs do not develop vertical stratification of more than 1^{o} F and do not have as great an effect upon downstream temperature as Lake Roosevelt. These reservoirs, however, are wider and deeper than the natural river and would be expected to alter the temperature regime. Jaske and Goebel, for example, have concluded that the construction of Chief Joseph Dam has resulted in a three-day delay of the water temperature maximum at Rock Island Dam (1967). Future temperatures

in this reach of the river will depend primarily upon release schedules at Grand Coulee Dam.

Priest Rapids Dam to the Snake River Confluence

Between Priest Rapids Dam and the Snake River confluence, a distance of 70 miles, the river is unimpounded. It is within this reach that the Hanford Works discharges high temperature cooling water from nuclear reactors. The Hanford Works is the largest identifiable source of advective heat on the Columbia River. No public information has been released on the discharge temperature or discharge rates because of classification requirements. However, Jaske (1969) has reported that from 1965 to 1967 the combined effects of Hanford and natural heat exchange contributed heat at the rate of 20,000 megawatts to the river between Priest Rapids and Richland. Without data on the thermal loadings at the Hanford Works, no realistic energy budget of the Columbia River downstream can be obtained.

The future temperature regime of this reach of the river will depend primarily upon thermal discharges from the Hanford Works. Other factors influencing the temperature will be upstream reservoir regulation for temperature control and power peaking and the proposed Ben Franklin Dam.

The Snake River Below Brownlee Dam

The Snake River has a significant influence upon water temperature in the Columbia River. In August, the month of maximum temperature, the Snake registers a temperature about 7^{o} F higher than that of the Columbia River near their confluence. Since the latter has a discharge of about six times that of the former, the temperature differential causes an average increase in the temperature of the Columbia River of about 1^{o} F. Changes in the thermal regime of the Snake River will therefore have an impact on temperatures in the Columbia River.

From a temperature standpoint, the lower Snake River is little affected by conditions above Brownlee Reservoir, and the 350 miles of the Snake River from the head of Brownlee Pool to the mouth can be considered as an independent unit. Flow regulation by Brownlee Reservoir has altered the natural temperature regime which previously existed at the damsite. The principal modifications have been the reduction in summer temperatures, the increase in fall temperatures, and a shift in the period of peak temperature from July to August.

Future temperature of the Snake River in this stretch will depend upon the operation of Hells Canyon Dam, Brownlee Dam, and, if one is constructed, any high dam in the Middle Snake.

Snake Confluence to Bonneville Dam

The 200-mile reach of the river from the Snake confluence to Bonneville Dam consists of four pools. These are formed by McNary, John Day, The Dalles, and Bonneville Dams. The pools are shallow and temperature surveys indicate they are well-mixed vertically, typical of river-run reservoirs. Analysis of temperature records at Bonneville Dam from 1938 to 1966 by Moore (1968) indicates that upstream dam regulation and water uses have had only a slight effect on the natural temperature regime at Bonneville Dam.

The future thermal regime of this reach will depend upon regulation of main stem reservoirs for temperature control and power peaking, and utilization of Snake River reservoirs for temperature control and irrigation.

Bonneville Dam to Astoria

The 146-mile reach of the Columbia River below Bonneville Dam is the only portion of the main stem in the United States which has no dams and in which none is proposed. In this reach, therefore, the Columbia River will continue to be a free-flowing stream.

Temperatures in this portion of the river are not presently influenced significantly by upstream reservoir operations or thermal loadings, and the prevailing regime can be considered as the natural temperature regime.

The future temperature regime of this reach will be influenced by flow regulation at Bonneville Dam for power peaking. Two thermal power plant sites have been proposed for this reach of the Columbia, one at Rainier on the Oregon side of the river, and one at Kalama on the Washington side.

The Willamette River

Peak flows in the Willamette River occur during the winter months of December, January, and February when the Columbia River is low. During this period the Willamette River discharge is one-third to one-half the Columbia River main stem discharge and could, therefore, have a significant effect upon the Columbia River's temperature. Under present conditions, however, temperatures of the two rivers at their confluence are within 2^{o} C of each other during the winter months.

During the summer months the Willamette River temperature may be as much as 3^{o} C higher than the Columbia, but the average discharge of the Willamette River is less than 10 percent of the Columbia River.

The future thermal regime of the Willamette will depend upon the regulation of main stem and tributary reservoirs.

V. MATHEMATICAL MODELS

In the Columbia River system five types of hydraulic environments can be recognized:

1. The deep reservoir in which the temperature varies in the vertical only. Examples of this type on the Columbia River main stem are the Arrow Lakes in Canada. In addition, there are numerous such reservoirs on tributary rivers. Hungry Horse on the South Fork of the Flathead in Montana, and Detroit Reservoir on the North Santiam in Oregon, are typical deep reservoirs.
2. The weakly stratified reservoir in which the longitudinal temperature variations are of the same order as the vertical variation. Lake Roosevelt, behind Grand Coulee Dam, is a reservoir with these characteristics.
3. River-run reservoirs in which the temperature is uniform in the vertical, but varies longitudinally. All the reservoirs on the main stem Columbia below Grand Coulee can be classified as river-run reservoirs, although some stratification has been observed in the pool behind Wanapum Dam.
4. The unimpounded reach between Priest Rapids Dam and the Snake River Confluence.
5. The Columbia River Estuary is that portion of the river which is influenced by tidal forces, and includes the entire stretch of the river from Bonneville Dam to the mouth.

Three models have been developed for the Columbia River Thermal Effects Study to simulate temperature in the five hydraulic environments. These models are based upon numerical solutions to the conservation laws of physics:

(1) Conservation of momentum

(2) Conservation of energy

(3) Conservation of mass

In their most general form, these mathematical differential equations are extremely difficult to solve. A general numerical solution to these equations is, in principle, possible. However, the development of ADP software and the amount of computer memory and execution time required make this approach impractical for a project such as the Columbia River Thermal Effects Study. In each of the models developed for this study, only those terms which are important for the transfer of momentum, heat and mass have been kept. These are determined from experience gained through laboratory and field experiments. The final test, of course, is whether or not the particular model is able to simulate the temperature in the appropriate environment.

The following sections describe the models that have been developed for the Columbia River Thermal Effects Study and the testing program conducted to establish their validity.

Deep Reservoir Model

Basic Equators and Assumptions

The method for simulating temperature in deep reservoirs is based upon a numerical solution of the one-dimensional form of the energy equation, where the reservoir is divided into horizontal layers.

$$\rho C_p \frac{A_j + A_{j+1}}{2} \frac{d\Theta_j}{dt} \Delta Z_j = \frac{A_j + A_{j+1}}{2} h_j \Delta Z_j + \rho C_p \{Q_{ij}\Theta_i - Q_{oj}\Theta_j\} - \rho C_p \{Q_{voj}\Theta_j - Q_{vij}\Theta_{j-1}\} + \rho C_p \left\{a_{j+1}A_{j+1}\frac{\overline{\Theta}_{j+1} - \Theta_j}{\frac{1}{2}(\Delta Z_j + \Delta Z_{j+1})}\right. - \left. a_j A_j \frac{\overline{\Theta}_j - \Theta_{j-1}}{\frac{1}{2}(\Delta Z_j + \Delta Z_{j-1})}\right\} \quad (4.1)$$

where

C_p = heat capacity of water

ρ = density of water

A_{j+1} = area of upper plane bounding the j^{th} element

A_j = area of lower plane bounding the j^{th} element

h_j = change in external solar heat flux per unit of water depth

A_{j+1} = coefficient of "effective" diffusivity at the upper boundary of the j^{th} element

A_j = coefficient of "effective" diffusivity at the lower boundry of the j^{th} element

ΔZ = thickness of the j^{th} element

Θ_j = temperature of the j^{th} element

θ_i = temperature of inflowing water

Q_{ij} = inflow to the j^{th} element

θ_{oj} = outflow from the j^{th} element

Q_{voj} = vertical transport through the top boundary of element j.

Q_{vij} = vertical transport through the bottom boundary of element j.

The following assumptions have been made:

1. All heat transfer occurs along the vertical axis.
2. All the heat advected to the reservoir by a fluid inflow is completely and instantaneously distributed throughout the horizontal element that receives this inflow.
3. Vertical exchange of heat due to turbulent processes can be modelled by a Fickian diffusion process. This diffusion process is characterized by an "effective" diffusion coefficient.
4. The level at which an inflowing source enters the reservoir is determined by finding where in the reservoir the inflow is neutrally buoyant. Temperature is the only factor used to determine the density.
5. Vertical distribution of temperature in outflowing water is determined from the experimental work of Debler (1959) and Craya (1949) depending upon the nature of the reservoir stratification.
6. The heat budget at the surface can be described by methods given in Wunderlich and Elder (1968).
7. The geometry of the model consists of finite segments developed from horizontal slices taken from the prototype.

8. No heat is transferred through the sides or the bottom of the reservoir.

9. Convective mixing occurs when the temperature gradient is below a critical value.

Given the initial temperature and time rate of temperature change, Equation (4.1) is solved numerically to obtain the reservoir temperature as a function of time and depth.

More specific detail regarding this model can be found in two publications by Water Resources Engineers, Inc.:

(1) Prediction of Thermal Energy Distribution in Streams and Reservoirs, prepared for the Department of Fish and Game, State of California, by Water Resources Engineers, June 1967.

(2) Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments, prepared for the Federal Water Quality Administration by Water Resources Engineers, December 1969.

Model Verification

Prototype reservoirs which have been used to verify the validity of this model include: 1) Folsom Reservoir in California; 2) Fontana Reservoir in North Carolina; 3) Hungry Horse Reservoir in Montana. The report, Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments contains the results of a simulation of Hungry Horse Reservoir as compared with observed values.

Data Requirements

The following data are required as input to the model:

1. Site Characterizations
   a. Depth-surface area curve
   b. Latitude
   c. Longitude
   d. Corrections for sunrise and sunset obstructions
   e. Reservoir altitude
2. Hydrologic Data
   a. Daily inflow from streams tributary to the reservoir
   b. Outflow from reservoir
   c. Initial reservoir surface elevation
3. Climatological Data
   a. Daily average of cloud cover
   b. Daily average of dry-bulb temperature
   c. Daily average of wet-bulb temperature
   d. Daily average of atmospheric pressure
   e. Wind speed at a height of 2 meters above the water surface.
4. Hydromechanical Data
   a. Coefficients for determining effective eddy diffusivity
   b. Light extinction coefficient
   c. Critical thermal gradient which determines when reservoir begins convective mixing

5. Water Temperature Data

   a. Initial reservoir temperature

   b. Initial rate of temperature change in the reservoir

   c. Daily average temperature of all inflows

River-Run Model

Basic Equations and Assumptions

This model has been developed to predict temperatures in regulated river impoundments which have only a small storage capacity and can be considered well-mixed. The model can be used in the estuary if it is well-mixed vertically, and if results in terms of temperatures averaged over a tidal period are sufficient.

The temperature in river-run reservoirs can be predicted from the one-dimensional energy equation.

$$\rho C_p U \frac{dT}{dx} = \frac{\Phi}{D} \tag{4.2}$$

where T -- the water temperature

U -- the longitudinal speed

Φ -- the flux of heat through the water surface

ρ -- water density

Cp - specific heat capacity of water

D -- the average depth of the reservoir

x -- longitudinal coordinate

The assumptions upon which this model is based are:

(1) The prototype reservoir is thermally well-mixed vertically and laterally.

(2) Longitudinal diffusion and dispersion can be neglected.

(3) The water surface profile between dams is a function of longitudinal distance only (water surface profile refers to the shape of the water surface as seen in a longitudinal section and does not imply an absolute surface elevation).

(4) Weather data from a representative station is adequate for describing conditions along the river.

(5) Empirically derived coefficients can be used to evaluate heat and mass transfer at the air water interface.

(6) The surface heat flux ϕ, composed of the following terms:

ϕs - net short wave radiation

ϕa - net atmospheric

ϕb - net emitted radiation from the water surface

ϕe - evaporative heat flux

ϕh - sensible heat conduction

(7) The surface heat flux can be written as a linear function of the water temperature, T:

$$\Phi = AT + B \qquad (4.3)$$

The coefficients A and B are obtained from a least-squares fit of the surface heat flux-water temperature curve. The rates of heating/cooling are determined from heat-flux calculations over a range of water temperatures which would include the expected maxima and minima. These calculations are based upon the work done by Wunderlich and Elder (1963).

If the speed, U, and the depth, D, are constant over a reach equation (4.2) permits a solution of the form:

$$T = (To + B/A)e^{\frac{Ax}{\rho C_p DU}} - B/A \qquad (4.4)$$

where TO is the initial water temperature.

If a heat source is encountered, the contribution is assumed to be completely mixed with the main stem. The main stem temperature is:

$$T = \frac{Q_m T_m + Q_t T_t}{Q_m = Q_t} \qquad (4.5)$$

where Tm, the mainstream temperature just upstream of the tributary is determined from equation (4.4) and Tt, the tributary temperature, is input data. Qm and Qt are the main stem and tributary discharges respectively.

The various parameters in equation (4.4) are updated for each new reach, daily period, and date. In this way downstream temperatures

are predicted in terms of the linear equation describing the heat flux, upstream water temperature, average water depth, advected sources and travel time.

The time of travel of water through each of the reservoirs is determined from a solution of the continuity equation. Input to this solution includes backwater curves for each reservoir as a function of time and cross-sectioned characteristics of the reservoir at several stations. Stations are spaced such that each reach is 5 to 10 miles long.

The model computes travel times and surface heat flux as the water moves through the ten projects from Grand Coulee to Bonneville Dam. Cumulative travel times and predicted temperatures are reported at selected points as the water moves downstream.

A complete description of this model, can be found in Working Paper #65, A Mathematical Model for Predicting Temperature in Rivers and River-Run Reservoirs published by the Federal Water Quality Administration, March 1969.

Model Verification

The river-run model has been used to simulate the temperature of the Columbia River for the periods July 22-31, 1966, August 20-September 12, 1967, and September 14-19, 1967. The result of these simulations are discussed in Working Paper #65.

Data Requirements

The following data is required to operate the model:

1. Site Characteristics
   a. Cross-sectioned area and water surface width at regular height intervals for selected river miles.
   b. Approximate latitude and longitude of river system.
   c. Altitude of reservoir.
2. Hydrologic Data
   a. Dam discharge at specified time intervals.
   b. Tributary inflows at specified time intervals.
   c. Reservoir backwater curves at specified time intervals.
3. Meteorological Data
   a. Cloud cover at specified time intervals.
   b. Dry bulb temperatures at specified time intervals.
   c. Wet bulb temperature at specified time intervals.
   d. Atmospheric pressure at specified time intervals.
   e. Wind speed at specified time intervals.
4. Water Temperature Data
   a. Initial river temperature at specified time intervals.
   b. Temperature of tributaries at specified time intervals.

Weakly Stratified Reservoirs

A segmented version of the deep reservoir model developed by Water Resources Engineers, Inc. was developed to simulate the more

complex temperature patterns found in the weakly-stratified prototype, Lake Roosevelt. The segmentation involved dividing the 150-mile long reservoir into six reaches. Vertical profiles of the longitudinal velocity were determined empirically. Inflows to a particular segment consisted of contributions from tributaries and the upstream segment.

While this model is not truly a two dimensional model it does account for longitudinal advection of heat. This is an important mechanism for heat transfer in Lake Roosevelt and gives rise to the tilted isotherms observed.

A more detailed description of this model can be found in the Water Resources Engineers publication, Mathematical Models for the Prediction of Thermal Energy Changes, prepared for the Federal Water Quality Administration.

Model Verification

This model has been used to simulate the temperature of Lake Roosevelt for the period July-October 1967. The results of this simulation as compared with the observed temperatures are presented in Mathematical Models for the Prediction of Thermal Energy Changes.

Data Requirements

The data requirements for this model are the same as those described in the section on the Deep Reservoir Model.

Estuary Model

Basic Equations and Assumptions

The processes governing heat exchange in the estuary are the same as those in the three reservoir types discussed in the previous sections. However, in the estuary tidal forces play an important role in determining the hydrodynamics. As a result, significant changes in velocities can occur in the estuary over a period of one tidal cycle. At some points in the estuary a reversal of the flow occurs on this same time scale. By contrast, in the regulated stretch of the river, which includes the reservoirs above Bonneville Dam, time scales associated with significant changes in velocities are of the order of days or months. To resolve the high-frequency changes associated with tidal effects, a time-dependent model for predicting the velocity distribution, as well as the temperature, is necessary.

Steady-state models have been developed (Thomann, 1963) for use in estuaries and have proved to be adequate for certain applications. In cases for which local effects are important, it is necessary to have the capability for predicting concentrations at regular intervals during the tidal cycle. For example, the maximum temperature resulting from a point discharge of heat may be considerably larger than the temperature averaged over a tidal cycle. The biological studies conducted as part of the Columbia River Thermal Effects Study illustrate the importance of thermal shock in determining the mortality rate of anadromous fish. The time-dependent model is

required to evaluate problems such as this.

The estuary model chosen for the Columbia River was originally developed by Water Resources Engineers, Inc. for the Federal Water Quality Administration, Southwest Region. It was adapted for use on the Columbia River estuary by personnel of the Pacific Northwest Water Laboratory.

The assumptions upon which the model is based are as follows:

1. The estuary is well-mixed vertically.
2. A network of one-dimensional elements with provisions to branch flows at nodal points gives an adequate representation of the estuary.
3. The one-dimensional equations can be used along each branch between node points.
4. Dispersion coefficients can be calculated from empirical equations (Fischer, 1968).
5. Surface heat fluxes can be calculated using methods described by Wunderlich and Elder (1968).

These assumptions lead to the following set of partial differential equations:

Continuity Equation

$$\frac{\partial(Au)}{\partial x} + B\frac{\partial H}{\partial t} = 0 \qquad (4.6)$$

Momentum Equation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial H}{\partial x} + Klulu = 0 \qquad (4.7)$$

Energy Equation

$$C_p \left\{\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} - \frac{\partial}{\partial x} \left(Dx \frac{\partial T}{\partial x}\right)\right\} = \Phi \qquad (4.8)$$

Where:

u is the horizontal velocity

g gravitational potential

H the water depth point

K roughness coefficient

B water surface width

A cross-sectional area

T temperature

Dx dispersion coefficient

x distance between nodes

t time

Φ heat sources

Equations (4.6) and (4.7) are converted to finite difference form and solved by the "leapfrog" method. In the "leapfrog" method, the initial conditions of velocity and depth are used to compute velocity from the Equation (4.6); the computed velocity is substituted in Equation (4.7) to obtain a new depth which is used as the

new initial condition to determine new velocities. The new velocity is again substituted into the continuity equation and the process continues.

The resulting velocities and water depths are edited and stored on tape for later use by the temperature model Equation (4.8). Solution of Equation (4.8), which predicts the temperature as a function of time, is accomplished by a finite difference scheme based on an explicit formulation.

A more detailed description of this model can be found in the Federal Water Quality Administration document, Mathematical Model of the Columbia River from the Pacific Ocean to Bonneville Dam, by R. J. Callaway, K. V. Byram, and G. R. Ditsworth, 1969.

Model Verification

Callaway, et al (1970) have described the verification of the temperature model in the estuary.

Data Requirements

1. Site characteristics
   a. cross-sectional area, water surface width, and distance between nodes.
2. Hydrologic data
   a. tributary inflows
   b. tidal elevation at estuary mouth
   c. Manning coefficients

3. Meteorological data

   a. cloud cover at hourly intervals

   b. dry-bulb temperature at hourly intervals

   c. wet-bulb temperature at hourly intervals

   d. atmospheric pressure at hourly intervals

   e. wind speed at hourly intervals

4. Water temperature data

   a. initial river temperature

   b. temperature of tributary inflows

VI. OPERATION OF MODEL

Temperature Simulation

Six temperature simulations of the combined weakly-stratified and river-run reservoir models were made using 1967 meteorology, hydrology and observed water temperature data. The estuary model was not used in these simulations because of the fact that it is used on a time scale different from the weakly-stratified and river-run reservoir models. The testing of the estuary model has been described by Callaway, et al (1970).

Meteorology from three cities, Spokane, Yakima, and Portland, was used to represent climatic conditions along the river. Spokane weather data was used from the Canadian border (river mile 740.0) to Rocky Reach Dam (river mile 474.5); Yakima weather data was used from Rocky Reach to Bonneville Dam (river mile 145.0); Portland weather data was used from Bonneville Dam to the mouth of the Columbia at Astoria.

The purposes of the test program were to:

1. Determine the accuracy of the models for predicting downstream temperatures.
2. Determine the effect of cold water releases at Grand Coulee Dam upon downstream temperatures.
3. Determine the effect of a constant 13,000 megawatt heat source in the Hanford area.
4. Determine model sensitivity to variations in the constants governing evaporative and sensible heat flux.

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5. Determine how the accuracy of the weakly-stratified model affects the accuracy of temperature predictions downstream.

To evaluate these problems six conditions were established. Predicted temperatures were compared with actual temperatures at various thermograph stations along the Columbia River. The conditions for the six simulations were as follows:

Case I.
1. 1967 meteorology and hydrology
2. 13,000 mw heat source in the Hanford area
3. temperature at Grand Coulee Dam predicted by weakly-stratified reservoir model
4. evaporation rate, $E=(a+bu)\ (e_s-e_a)$, where u is the wind speed in meters per second, e_s the saturation vapor pressure in mb, and e_a, the ambient vapor pressure in mb, was determined with a=0.0 and $b=1.0\times10^{9}$ mb-1.

Predicted temperatures compared with actual temperatures at six locations are shown in Figure 2. The mean and standard deviation of the error is shown in Table 5.

Case II.
1. 1967 meteorology and hydrology
2. 13,000 mw heat source in the Hanford area
3. 1967 observed temperatures at Grand Coulee Dam used as input to the river run reservoir model.
4. evaporation rate determined with a=0.0 and $b=1.0x^{-9}$ mb-1.

Predicted temperatures compared with observed temperatures at six locations are shown in Figure 3. The mean and standard deviation of the error are shown in Table 5.

Case III. 1. 1967 meteorology and hydrology

2. no heat source in the Hanford area

3. 1967 observed temperatures at Grand Coulee Dam used as input to the river-run reservoir model

4. evaporation rate determined with a=0.0 and b=1.0×10^{-9} mb-1

Predicted temperatures compared with observed temperatures at six locations are shown in Figure 4. The mean and standard deviation of the error are shown in Table 5.

Case IV. 1. 1967 meteorology and hydrology

2. 13,000 mw heat source in the Hanford area

3. 1967 observed temperatures at Grand Coulee Dam used as input to the river-run reservoir model

4. evaporation rate determined with a=0.0 and b-1.0×10^{-10}

Predicted temperatures compared with observed temperatures at six stations are shown in Figure 5. The mean and standard deviation of the error are shown in Table 5.

Case V. 1. 1967 meteorology and hydrology

2. 13,000 mw heat source in the Hanford area

3. 1967 observed temperatures at Grand Coulee Dam used as input to the river-run reservoir model

Table 5

MEAN, (μ) AND STANDARD DEVIATION, (σ) IN DEGREES FAHRENHEIT FOR THE DIFFERENCE BETWEEN SIMULATED AND OBSERVED TEMPERATURES AT SIX LOCATIONS ON THE COLUMBIA RIVER. SIX DIFFERENT CASES OR SIMULATIONS WERE MADE.

	Case I		Case II		Case III		Case IV		Case V		Case VI	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Rocky Reach Dam	-1.2	2.4	-0.1	1.0	-0.1	1.0	1.2	2.3	-5.9	7.7	-4.4	4.5
Priest Rapids Dam	-1.0	2.2	-0.1	1.1	-0.1	1.1	1.7	3.3	-6.5	8.0	-4.0	4.2
Confluence of the Snake River	-0.6	2.4	0.1	2.1	-2.1	2.7	2.5	4.7	-6.9	8.2	-3.4	4.1
McNary Dam	-0.5	1.7	-0.5	1.3	-1.4	1.8	1.4	2.4	-6.7	7.8	-2.3	2.7
Bonneville Dam	-0.3	1.8	-0.3	1.5	-1.0	1.7	2.8	4.4	-8.8	9.8	-1.9	2.6
Beaver Army Terminal	0.8	1.8	0.2	1.5	0.7	1.7	3.7	5.1	-6.0	6.6	-0.7	2.1

4. evaporation rates determined with a=0.0 and b=1.0×10^{-8}

Predicted temperatures compared with observed temperatures at six stations are shown in Figure 6. The mean and standard deviation of the error are shown in Table 5.

Case VI. 1. 1967 meteorology and hydrology

2. 13,000 mw heat source in the Hanford area

3. 1967 observed temperatures at Grand Coulee Dam minus 5.0° F used as input to the river-run reservoir model

4. evaporation rates determined with a=0.0 and b=1.0×10^{-9}

Predicted temperatures compared with observed temperature at six stations are shown in Figure 7. The mean and standard deviation of the error are shown in Table 5.

Discussion of Temperature Simulations

Case I. The purpose of this simulation was to determine the accuracy with which the combined weakly-stratified and river-run reservoir model could simulate water temperature in the Columbia River. Hydraulic, hydrologic and meteorologic data from 1967 were used and a constant heat source of 13,000 mw was added in the Hanford area. The evaporation rate was determined from the equation $E=(a+bu)(e_s-e_a)$, with a=0.0 and b=$1.0 \times 10^{-9} mb^{-1}$. The results of the simulations at six locations, for the period April 1 to November 30, 1967, are shown in Figure 2.

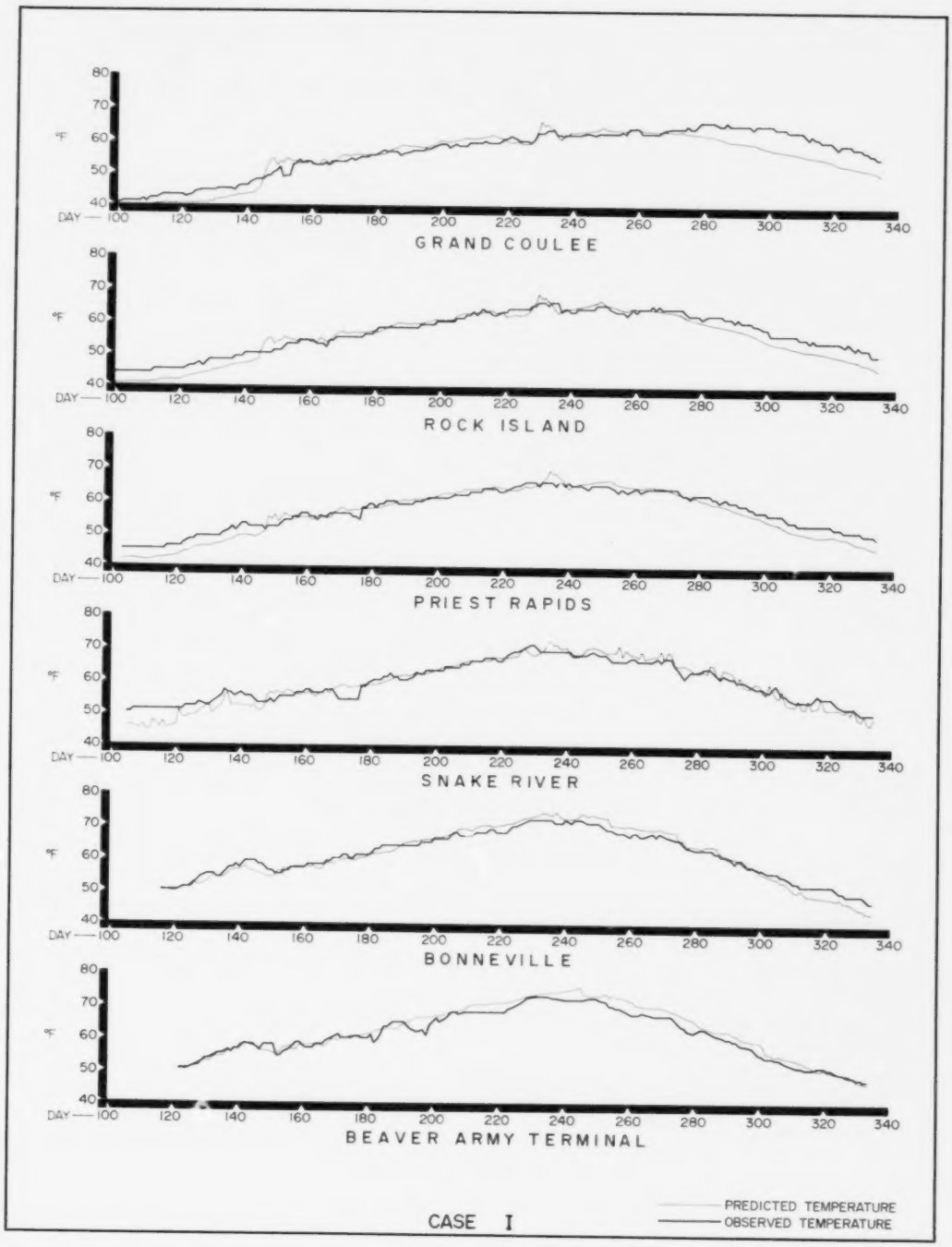

Figure 2. Simulated and Actual Temperatures (1967) in the Columbia River at Six Locations, Case I.

From June 1 to October 1 the combined models simulate temperatures well. However, the weakly-stratified model anticipates the fall overturn in Lake Roosevelt by about two weeks and simulated temperatures at Grand Coulee Dam are considerably lower than observed temperatures from this time until the first of May.

Comparing the mean error (Table 5) in this simulation with the mean error for Case II, in which observed temperatures at Grand Coulee Dam were used as initial conditions, it can be seen that the weakly-stratified model's contribution to the mean error decreases downstream. This can be attributed to the fact that any simulated water temperatures at Grand Coulee Dam which are not in equilibrium with the calculated atmospheric heating/cooling rates will tend toward equilibrium as the water proceeds downstream. Therefore, any errors at Grand Coulee Dam, resulting from the use of the weakly-stratified model, are essentially in equilibrium with the calculated atmospheric heating/cooling rates by the time the water parcel reaches McNary Dam. Any errors in the simulation at that point would be due to incorrect atmospheric heating/cooling rates, imprecise knowledge of heated discharges, and errors in predicting the travel time of water parcels.

Case II. The purpose of this simulation was to determine how effectively the river-run model could be used to simulate daily-averaged temperatures from Grand Coulee Dam to the mouth of the Columbia River at Astoria, Oregon. Conditions for this simulation were the same as in Case I, except that the observed temperature

at Grand Coulee Dam were used as initial conditions. Simulated temperatures were compared with observed temperatures at six locations and the results are shown in Figure 3.

From Table 5 it can be seen that the difference between simulated and observed temperatures at Rock Island and Priest Rapid Dams each show a mean of -0.1^{o} F, and a standard deviation of 1.0^{o} F and 1.1^{o} F, respectively. At the confluence of the Snake River, below the Hanford Area, the mean difference between simulated and observed is still small, -0.1^{o} F, but the standard deviation, 2.1^{o} F, has increased 100 percent from upstream values. This result implies that while 13,000 megawatts may be a good average value for the heat input due to Hanford, deviation from this value makes it difficult to simulate temperatures accurately on a short-term basis. However, as in the case of the weakly-stratified model, errors introduced due to imprecise knowledge of the Hanford discharge, are attenuated as the simulation proceeds downstream.

Comparison of this simulation with Cases IV and V, which are identical, except for the coefficients used to calculate the evaporation rate, indicate that the values $a = 0.0$ and $b = 1.0 \times 10^{-9}$ mb^{-1}, in the equation, $E = (a + bu)(e_s - e_a)$ gives the best results. This corresponds closely to the value found in the Lake Hefner Study (1954), where the values $a = 0.0$ and $b = 1.16 \times 10^{-9}$ mb^{-1} were obtained.

Case III. The purpose of this simulation was to estimate the average temperature increase resulting from the introduction of

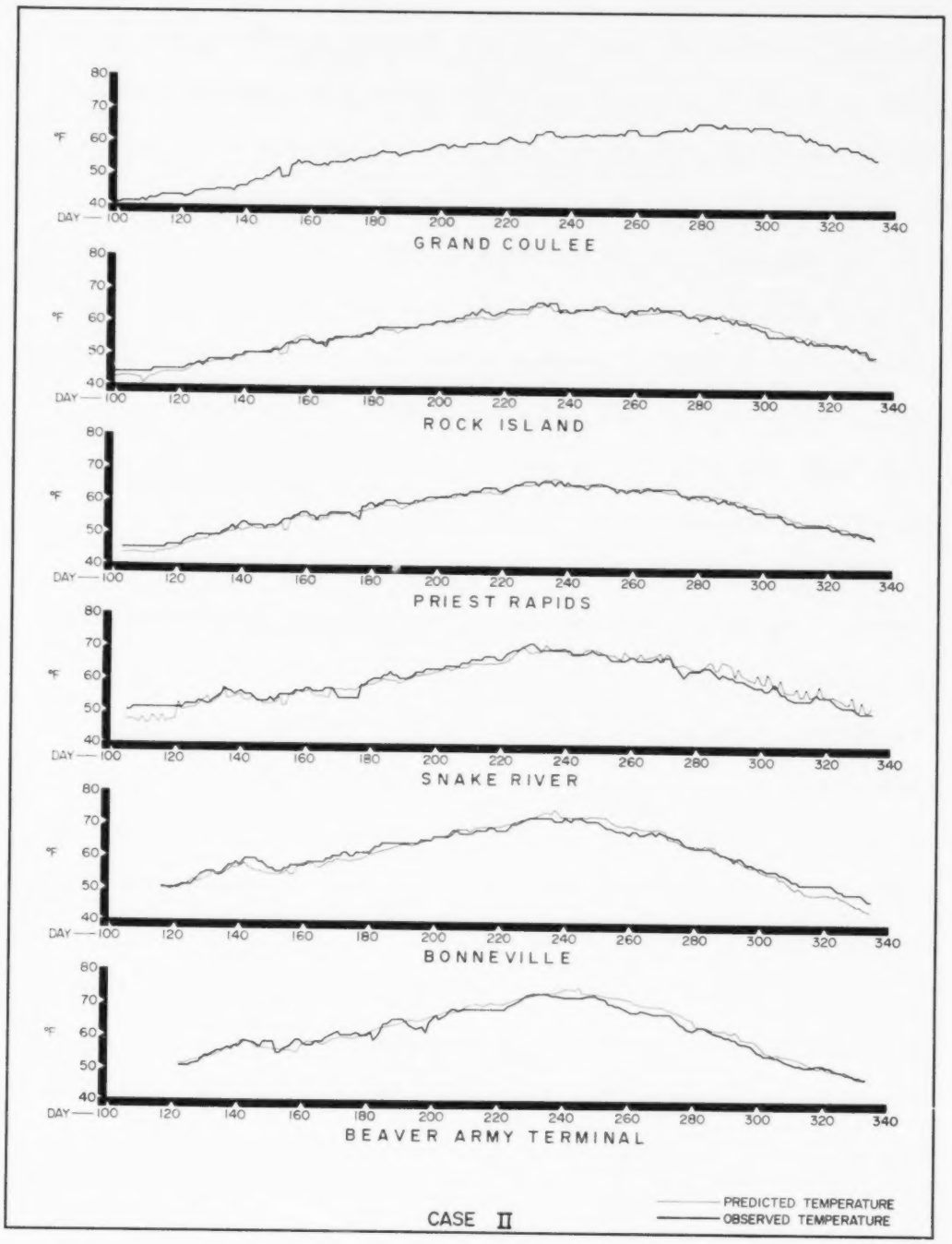

Figure 3. Simulated and Actual Temperatures (1967) in the Columbia River at Six Locations, Case II.

heated water at Hanford. The conditions for this simulation were identical to those of Case II, except that no heat was added to the river at Hanford. The results of the simulation compared with observed temperatures at six locations on the Columbia River are shown in Figure 4.

The estimated average increase in 1967, at the confluence of the Columbia and Snake Rivers from April 1 to November 30 was 2.2° F; at McNary Dam 1.1° F; at Bonneville Dam 0.7° F, and at the Beaver Army Terminal -0.1°F. The error associated with the estimate at the Snake River was ± 0.5° F; at McNary Dam, Bonneville Dam, and the Beaver Army Terminal the error was ± 0.2° F.

Case IV. The purpose of this simulation was to determine how sensitive the river-run model was to lowering the evaporation rate by an order of magnitude, as compared to the results obtained in the Lake Hefner Study (1954). Conditions for this simulation were identical to those of Case II, except that the coefficients in the equation for determining the evaporation rate, $E = (a + bu)(e_s - e_a)$, were $a = 0.0$ and $b = 1.0 \times 10^{-10}$ mb^{-1}. Simulated temperatures are compared with observed temperatures in Figure 5.

The results of this simulation indicate that, on the average, simulated temperatures are higher than the observed temperatures. The mean difference varies from a minimum of +1.2° F at Rock Island to a maximum of 3.7° F at the Beaver Army Terminal.

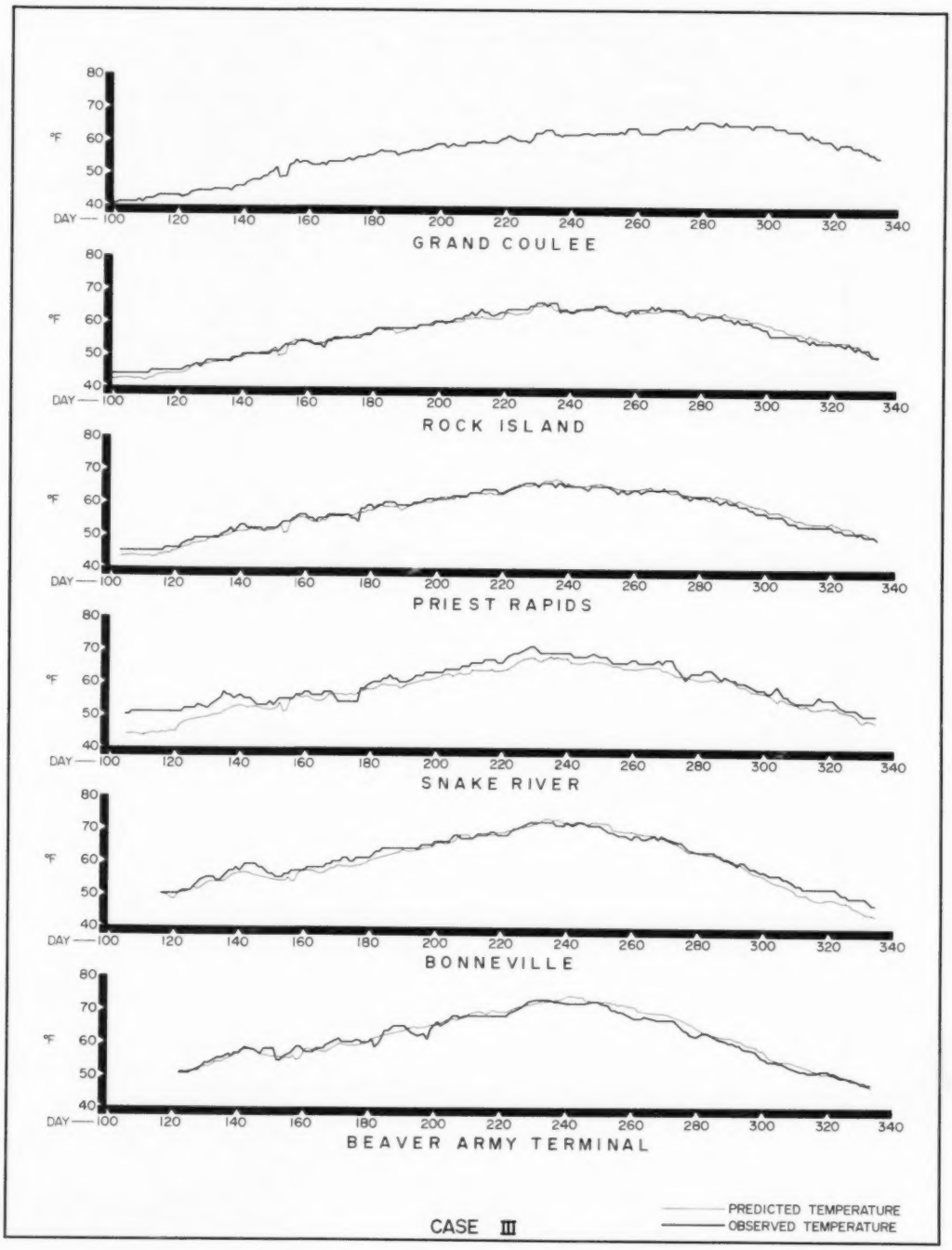

Figure 4. Simulated and Actual Temperatures (1967) in the Columbia River at Six Locations, Case III.

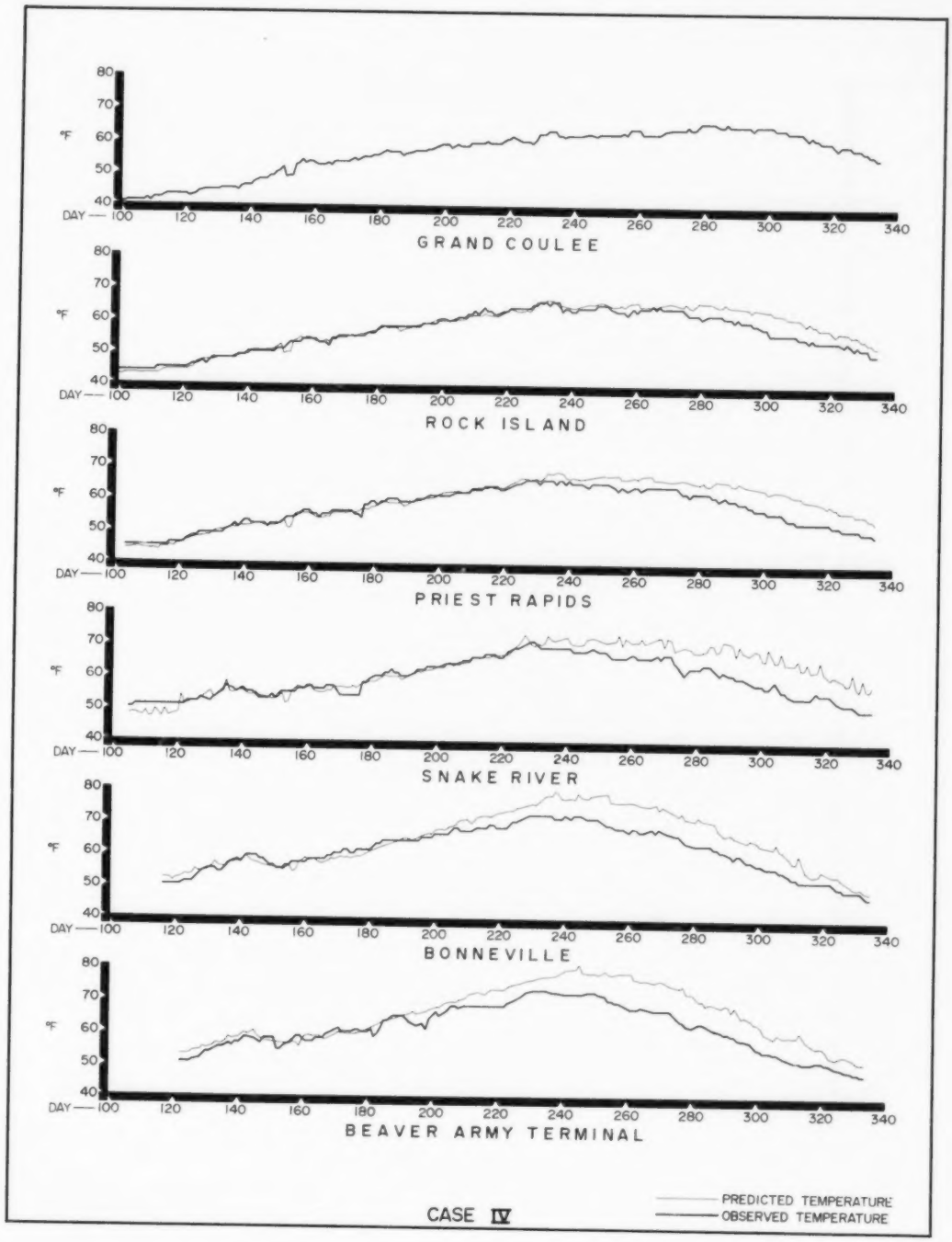

Figure 5. Simulated and Actual Temperatures (1967 in the Columbia River at Six Locations, Case IV.

It is interesting to note that during the warming part of the cycle, from the first of April to the end of August, the error introduced by decreasing the evaporation rate is small. The major contribution to the difference between simulated and observed occurs after the first of September when water temperatures are decreasing.

Case V. The purpose of this simulation was to determine how sensitive the river-run model was to increasing the evaporation rate, compared to results obtained in the Lake Hefner Study (1954). In this simulation the coefficients in the evaporation equation were $a = 0.0$ and $b = 1.0 \times 10^{-8}$ mb^{-1}. Results at six locations are shown in Figure 6.

The increased heat loss resulted in simulated temperatures substantially lower than observed temperatures at all locations. The average difference between simulated and observed was a minimum at Rock Island Dam, -5.9° F, and a maximum at Bonneville Dam, -8.0° F.

Once again, the simulation appeared to be more sensitve to the evaporation rate during the period when water temperatures were decreasing.

Case VI. The purpose of this simulation was to determine how far downstream the effects of cold water releases at Grand Coulee Dam could be observed. The conditions for this simulation were identical to those of Case II, except that the observed temperatures

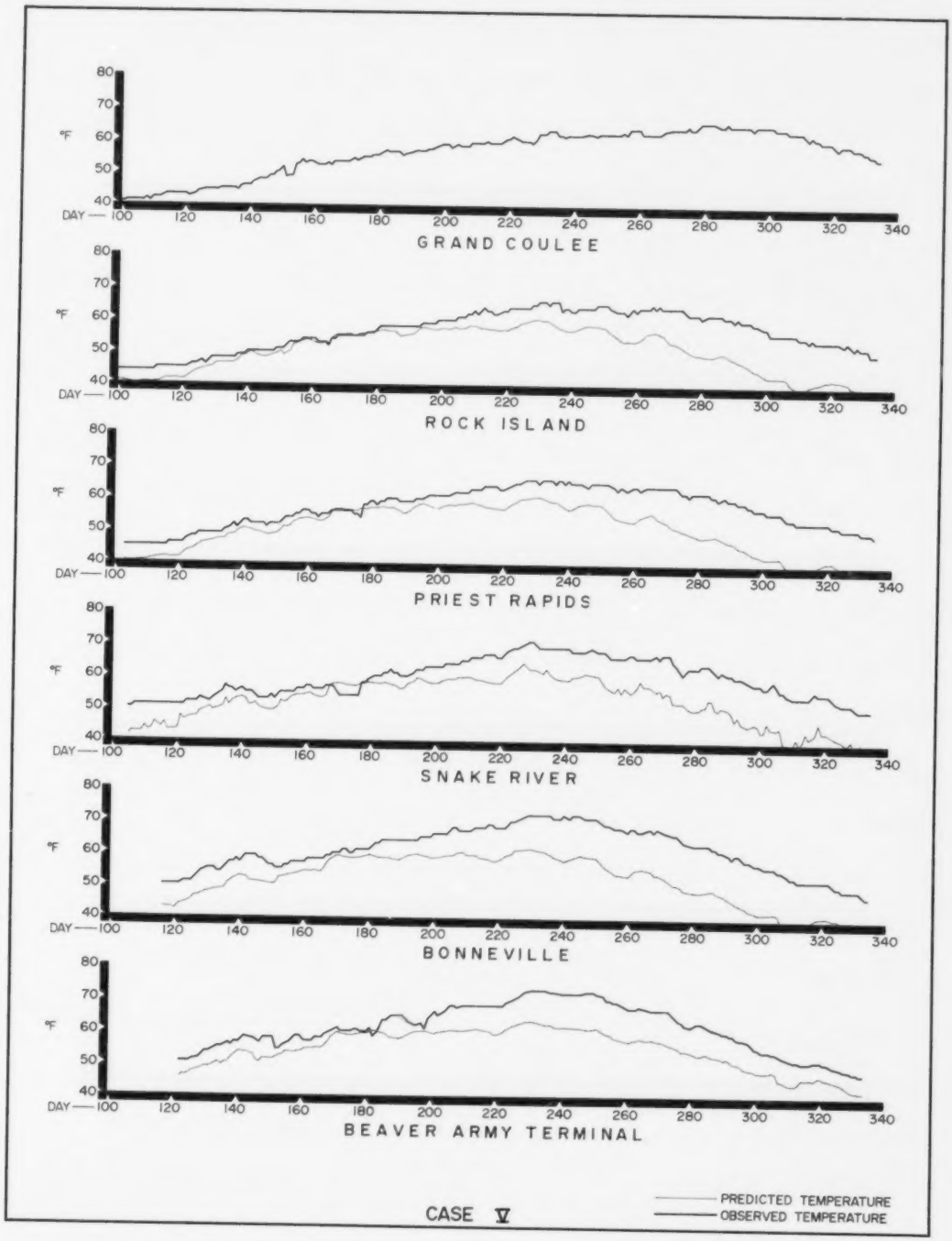

Figure 6. Simulated and Actual Temperatures (1967) in the Columbia River at Six Locations, Case V.

at Grand Coulee Dam were arbitrarily reduced 5° F. The amount of temperature control available from the natural stratification of Lake Roosevelt varies considerably during the season and this test was not meant to imply that 5° F temperature control could always be obtained. However, developments in the future, such as use of Canadian storage may increase the amount of temperature control. Importantly, this simulation provides some idea of the benefits which might be obtained by decreasing water temperature at Grand Coulee Dam during the entire season. Simulated temperatures compared to observed temperatures at six locations are shown in Figure 7.

The results of the simulation indicate that on the average 84 percent of the cold water released at Grand Coulee Dam is available at Rock Island, 78 percent at Priest Rapids, 70 percent at the Snake confluence, 36 percent at McNary, 32 percent at Bonneville, and 18 percent at the Beaver Army Terminal. As can be seen from the graphs, the amount varies with the season. During the period of increasing water temperatures, the amount of benefit available from the cold water releases at Grand Coulee is greater than during the period of decreasing temperatures.

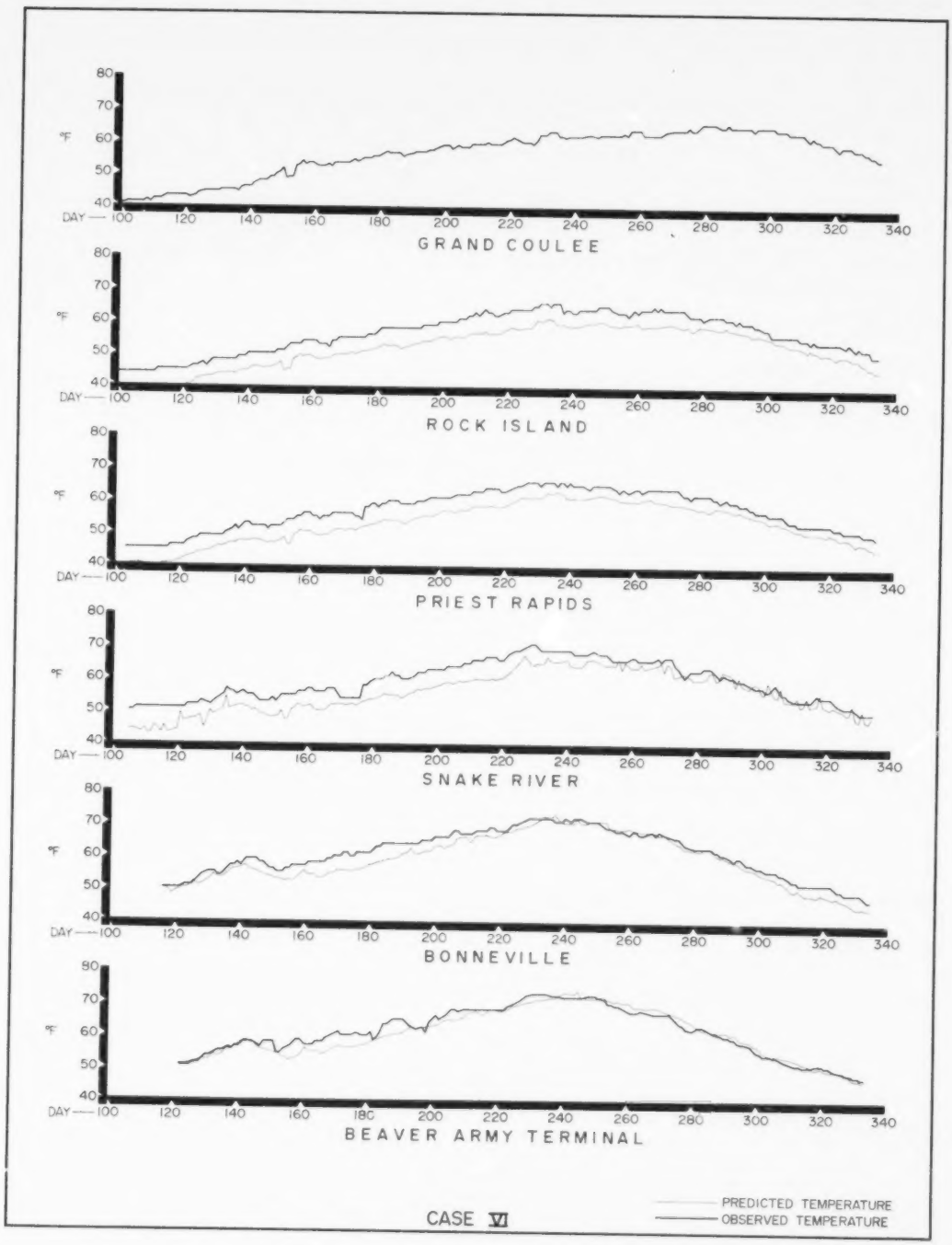

Figure 7. Simulated and Actual Temperatures (1967) in the Columbia River at Six Locations, Case VI.

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